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Multi-agent systems for reactive power control in smart grids

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ABSTRACT

Power system monitoring is the most fundamental prerequisite for making reasonable decisions in a control center. In recent years, with the advent of smart grids, monitoring and control of reactive power in power systems has entered a new era. This issue have highlighted the need for effective methods of decentralized optimal reactive power control (DORPC), especially based on the new available frameworks which have emerged along with the smart grids. This paper presents a novel approach to the DORPC problem based on a Holonic architecture. The Holonic architecture has some unique features by which the objective of the DORPC problem could be optimized through a timely proposed strategy. In order to demonstrate the features of the proposed approach, it is compared with two other methods considering a set of indices. Accordingly, the proposed approach has great potential to reduce the active power losses and to fully exploit the available reactive power resources. It requires a limited set of data while improves the fault tolerance of the network.

Introduction

Motivation

The proliferation of distributed energy resources (DERs) in future distribution networks brings about formidable challenges regarding their reactive power control. Roughly speaking, the advent of future smart grids changes the paradigm in power system operations. One of the most fundamental prerequisites of such grids is to employ distributed algorithms by means of data exchange among several entities [1]. Traditionally, power systems are operated on the basis of a control center where a certain set of quantities of the network is gathered via a supervisory control and data acquisition (SCADA) system. Such schemes, nonetheless, will no longer effectively manage a distribution network hosting the sheer number of meters, sensors, actuators, and DERs [2]. In the centralized schemes, the burden associated with a large number of entities could bring about congestion of communication infrastructure or crash of central processors. Moreover, the power system operation becomes more vulnerable in case of a fault occurrence in the communication link. Indeed, the heavy dependence of centralized methods to the communication link leads to a significant interruption in the system control if any fault occurs in the communication link. Consequently, shifting from a centralized operation to a decentralized one would considerably enhance the real-time control of smart grids and improve their supply resilience [1,3].

The reactive power control plays a vital role in the optimal operation of power systems. Insufficient reactive power is considered to be one of the major reasons for recent blackouts and voltage collapses around the world [4]. Generally, an optimal reactive power control scheme seeks to determine the optimum values of controllable variables (e.g., the voltage of generators, on-load transformer tap-changers (OLTC), reactive power compensators, distributed generations (DGs), and smart parks) so as to minimize an objective function. From a computational perspective, reactive power control is a nonlinear optimization problem with a set of complicated constraints. The main goals of the reactive power control problem, which have been addressed in the literature, are reduction of active power losses, minimization of voltage deviations, and enhancement of voltage stability margin [5].

Literature review and contributions

A large body of literature has investigated the reactive power control problem. In [5], a novel method is presented in order to solve a multi-objective reactive power control problem. The method considers bus voltage limits, the limits of branches power flow, generator voltages, transformer tap changers and the amount of compensation on weak buses. The objectives of the optimization problem are real power losses and voltage deviations from their corresponding nominal values. In [6], the authors have proposed a probabilistic algorithm for optimal reactive power provision in

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hybrid electricity markets. The proposed algorithm is a six-stage multi-objective optimization problem which also takes the load forecasting errors into account. The authors in [7,8] have used smart grid technologies in order to collect measurements and send directions through a secure communication infrastructure. In these papers, a hierarchal intelligent voltage control framework based on incident command system (ICS) is proposed in two different structures: a central control scheme and a local control scheme. Note that these structures are proposed in order to provide a real and reactive power support at the end-use level.

In the decentralized scheme proposed in [9], agents are allowed to determine the injection of reactive power in the network. Fazio et al. [10] proposed a decentralized approach which is mainly based on an off-line coordination and optimal set-point design for the reactive power control scheme of the DGs. In [11], a model-free decentralized voltage control algorithm is proposed with the aim of minimizing the power loss of an islanded microgrid. The algorithm works well even when the configuration of the microgrid changes. In [12], a distributed multi-agent scheme is presented for reactive power management in smart coordinated distribution networks with DERs. A multi-agent method is proposed for emergency control of long-term voltage instability in a multi-area power system [13]. In this study, the overall problem is partitioned into a set of sub-problems, each to be tackled by an individual agent.

This paper aims to establish a decentralized optimal reactive power control (DORPC) scheme in smart grids. The proposed methodology is developed based on a Holonic architecture which is capable of combining both autonomous and cooperative behaviors efficiently in order to attain the system goals. Such capabilities would considerably alleviate the concerns associated with the centralized approaches. Employing the proposed architecture, system operators will be able to operate the network near to the optimal point. Considering the two unique features of the Holonic structure (i.e., the Holon dynamics and the Holonic negotiations), this methodology would fully exploit the available reactive power sources in the network. The prevailing uncertainties pertaining to renewable energy sources (RES) are also taken into account. In order to evaluate the performance of the proposed approach, it is compared with two other methods. Meanwhile, the authors of this article have previously proposed a decentralized architecture for optimal reactive power dispatch in their prior work [14]. As a follow-up, this paper presents a more refined use case to illustrate the effectiveness of the proposed scheme in the context of smart grids. Generally speaking, some main contributions of the proposed DORPC structure is as follows:

- Developing a hierarchical decentralized approach in order to control the reactive power flows.
- Proposing an approach to avoid a surplus of communication between different areas of the system.
- Obtaining a DORPC by a low time-consuming method together with few control actions during the proposed strategy.
- Developing an appropriate test bed to validate the scheme in a realistic setting by linking MATLAB and java agent development framework (JADE) platforms to each other.

Paper organization

The rest of this paper is organized as follows. Section ''Multi-agent systems (MASs) in smart grids'' briefly introduces the basic concepts of the Holonic structure as a novel MAS in power grids. Section ''Formulation of the DORPC problem'' is devoted to the mathematical formulation of the problem. The decentralized approach used to solve the problem is presented in Section ''DORPC based on the Holonic structure''. The prevailing uncertainties along with the Plug-in electric vehicle (PEV) modeling are presented in Section ''Formulation of the DGs and PEVs''. Simulation results are discussed in Section ''Numerical studies''. Finally, relevant concluding remarks are provided in Section ''Conclusion''.

Multi-agent systems (MASs) in smart grids

MAS concept

A MAS is composed of intelligent agents for harmonization of their behavior. The residence in an environment and autonomy are the common concepts expressed for agents [15]. The agent's environment is all things located at its outside and surroundings. Generally, the agent's interaction with its environment can be seen as a succession of perception, decision-making, and measures [16]. An autonomous agent is an agent whose decisions depend not only on the perception of environment, but also on the prior knowledge (a set of predesigned actions) provided in the design step [17]. The reactivity, pro-activity and social ability are other features of agents [16]. Reactivity means agents' ability to perceive their environment and respond timely to the changes occurred in the environment so as to satisfy design objectives. The agents' proficiency to mutate their behavior dynamically means the pro-activity. For example, if the connection between agent-1 and agent-2 is lost, agent-1 will look for another agent which serves the same services. This feature indicates the agent's initiative. The social ability is beyond the data transfer between various software and hardware. In fact, it shows agent's ability for cooperative negotiation and interaction.

Now, the obvious question that may come to mind is: when MAS can be suitable for solving a problem? This question is answered by defining several determinant indexes including: (1) the environment should be uncertain, complex and open and/or high dynamic, (2) using agents should be seen natural, (3) data, control and authority must be distributed, (4) the system must possess tolerance and strength and (5) it should be able to execute calculation simultaneously in parallel.

MAS organization

The MAS organization is a set of roles, interactions and authority structure that handles MAS's behavior. Analogous to human organizations, a MAS organization determines how agents interact with each other not only in real time, but also in long-term interactions. This organization can touch the authority relationships, resources allocation, information flow, coordination patterns and other system characteristics. Thus, a simple group of agents may represent complex behavior and/or a sophisticated group of agents reduces the complexity of their behavior. This definition shows that the shape, size, and features of an organizational structure can impress the system behavior. Many organizational structures are presented by researchers in this filed. A comprehensive review of these organizations is provided in [18].

Notion of Holon

The concept of "*Holon*" was introduced for the first time by a Hungarian philosopher for describing recursive and self-similar structures in the biological and social organizations [19]. A Holon is a self-similar structure and a stable integrated fractal which can be composed of several smaller Holons (i.e., sub-Holons) and on the other hand, it can be a component of a bigger Holon (i.e., super-Holon). According to this recursive definition, a Holon can be seen, depending on the level of observation, either as an autonomous "*atomic*" entity, or as an organization of Holons. A hierarchical organizational structure of Holons is called Holarchy. The Holon has several features including [20,21]: (1) autonomy (state, action and computational autonomies): agents' autonomy means that agents control their actions and internal states which enables them to operate without the direct intervention of humans or others, (2) Common goal dependent behavior: all sub-Holons should pursue at least one common goal while pursue their personal goals, (3) Increased group capabilities: it means the extended capabilities of agents at the group level (*macro* actions). Therefore, a super-Holon may have capacities that its sub-Holons do not have them. (4) Belief: agents have implicit and/or explicit representations of their environment. The belief's requirements remain unchanged, (5) bounded rationality: a Holon has to behave optimally with respect to its limited resources and its goals and (6) communication: this has an important role in Holons' autonomy. In the Holarchy structure, communication can be established between Holons by heads, also between head and sub-Holons under the head supervisory. They are known as *Intralevel* communication and *Interlevel* communication respectively [22].

Generally, the Holonic MAS is represented via the role interaction organization (RIO) model [20,22]. This model is established based on three interrelated concepts: role, interaction, and organization. Roles are general behaviors. They can interact mutually pursuant to the interaction mold. In fact, this model which classifies general behaviors and their interactions, will vocalize an organization. Thus, the organization is known as a coordination structure. With these explanations, there are two important aspects to model the Holonic structures based on RIO: Holonic organization and goal-dependent interactions.

Holonic organization

Holons are organized internally to generate and manage a super-Holon based on three different structures: the federation of autonomous agents, moderated group, and fusion [20,21]. The degree of sub-Holons' autonomy is their main difference. In this paper, the moderated group is employed for organizing Holons. The reason behind this choice is the wide range of configurations which can be created by mutating the commitments of sub-Holons toward their super-Holon. A schematic plot of Holons' autonomy degree is illustrated in Fig. 1.

In the moderated group structure, there are two different statuses for sub-Holons: (1) moderator; that communicates with outer Holons and (2) represented Holons; who are supervised by their moderator. Also in this structure, four roles are defined for members of a Holon: head, part, multi-part and standalone. For a super-Holon, the head role is belonged to the moderator; and the part and multi-part are represented members. Multi-parts belongs to several Holons, while a part belongs to only one Holon. Standalones show non-member Holons. They can negotiate with heads to enter the Holon. Head's communications with its parts are from command/request types. Fig. 2 schematically shows the Holonic roles.

Goal-dependent interactions

The definition of interactions between members of a group is a crucial topic neglected in the literature. These interactions are known as goal-dependent (also referred to as goal driven or goal directed) interactions. Each Holon needs ploys to acquire its targets. Therefore, an internal organization (called goal-dependent interactions) is obligatory to distribute tasks and information between sub-Holons. The Holonic non atomic agent contains:

- A unique Holonic group: it is a sample of Holonic organization that describes the members' organization way. All members of the (super-) Holon should belong to this group.
- A set of groups: it is a sample of internal organization (goal-dependent groups) created based on the aims/tasks of the members. The coordination of members' interactions is its main purpose. It may only include a sub-set of super-Holon's members.

The basic paradigm of the internal organization is clearly presented in Fig. 3.

Holon dynamics

One of the attractive particularities of the Holonic organization is its dynamism which can be expressed in two states: (1) creation and integration of new members called *merging* and (2) self-organization.

Merging refers to a super-Holon creation process which can be executed either by merging a set of existing Holons into a super-Holon or by decomposing a Holon to several Holons. In the proposed structure, it is assumed that the super-Holon is capable to define the interactions of its members. Thus, the decomposition of a Holon will not occur. In the proposed Holarchy, the merging interaction is considered to be a specific interaction between two Holons which desire to create a super-Holon. Generally, there are two kinds of merging in the Holarchy, including creation a new super-Holon and joining to a super-Holon. The former can be occurred by three approaches: Predefined, Negotiation and Evolutive. The details of these approaches can be found in [22].

As mentioned earlier, the roles indicate the status of the components inside a super-Holon. The transitions between roles play an

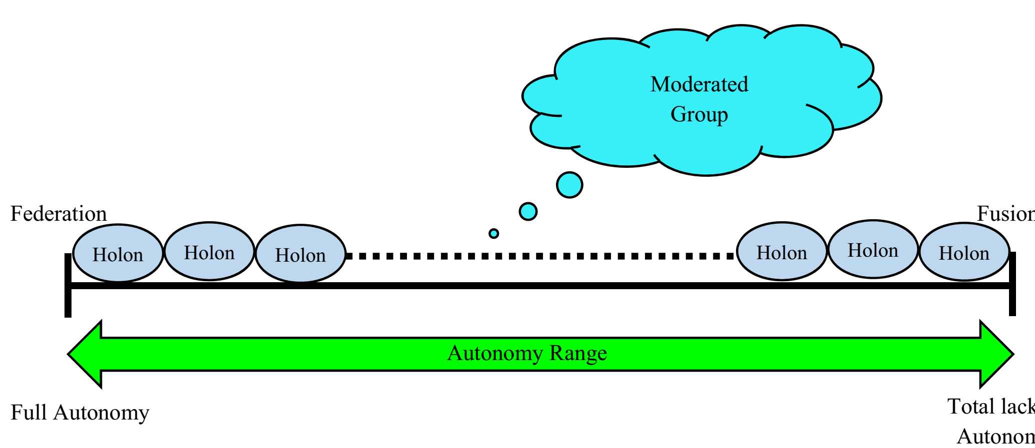

Fig. 1. Autonomy of Holons.

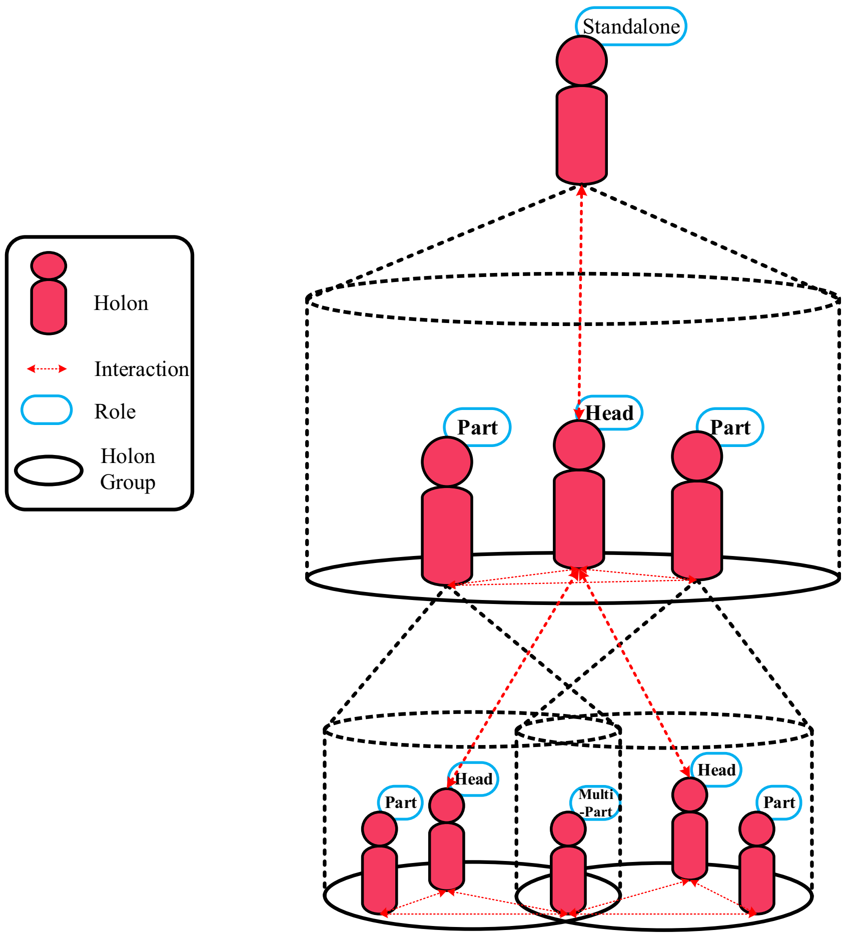

Fig. 2. Holonic roles according to the moderated group structure.

important role in this regard. Specifically, they can help the Holonic structure so as to adapt to different conditions. The *readjustment* of the roles (for example, the head role) is an aspect of self-organization. It means that a role can be allocated to another Holon based on the current situation. This unique feature of the Holarchy increases its flexibility.

On the other hand, the *compatibility* of two Holons is a basic requirement for the self-organization capability. In general, if two Holons have common aims, they will be compatible. Furthermore, the *affinity* and *satisfaction* are defined as two criteria of *compatibility* [22]. The *Affinity* refers to the compatibility measurement of two Holons to operate toward a common aim. The *satisfaction* is defined as the development value of a Holon toward its purpose which can be classified into four categories based on the actions of the other agents: (1) Self-Satisfaction (*SS*), which is related to the Holon's own work, (2) Collaborative Satisfaction (*CS*), which is related to the Holon collaboration with the other members of a Holon, (3) Accumulative Satisfaction (*AS*), which is calculated based on the collaboration with the members of a multiple super-Holon and (4) Instant Satisfaction (*IS*), which is the current satisfaction. In this paper, the instant satisfaction is considered as follows:

$$\forall k \in \text{Holonic MAS} \quad IS_k = \left\{ \begin{array}{ll} CS_k + SS_k & \text{if } ROL_k = \text{Part} \vee ROL_k = \text{Head} \\ AS_k + SS_k & \text{if } ROL_k = \text{Multipart} \\ SS_k & \text{if } ROL_k = \text{Standalone} \end{array} \right\} \tag{1}$$

$$AS_k = \sum_s CS_k^s \quad \forall s \in SuperHolon(k) \tag{2}$$

where, SS_k is self-satisfaction of kth Holon; CS_k is the collaborative Satisfaction of kth Holon; AS_k is the cumulative satisfaction of kth Holon; IS_k is the instant satisfaction of kth Holon; ROL_k is the role played by kth Holon.

Holonic negotiation

Holons can negotiate with each other to achieve their goals. Ref. [23] has introduced seven properties for a negotiation protocol such as simplicity and stability [23]. Meanwhile, several negotiation protocols have been proposed for MASs [24–26]. In general, they can be classified into two categories, i.e., individual rationality and social rationality. In the former, agents trace improvement of their *utility* function regardless of the social behaviors. In the latter, agents are able to balance between their social behavior and self-interest. In this paper, the individual rationality is selected as the negotiation protocol. Holons negotiate for a set of *preferentially independent* issues (N_{issue} = number of issues) [27,28]. If $N_{issue} < 3$, Holons negotiate for each of them separately. For $N_{issue} > 2$, a subset of issues is selected. In this paper, three parameters is defined for the negotiation, {*quantity*, *quality and price*}. Assume that Holon H^* negotiates with a sub-set of Holons on a sub-set of issues ($\aleph^*$) called the *negotiate set*. A permissible limit (Γ) is considered for each issue. Subsequently, a value function ($\Re$) is employed so as to prioritize the issues. The net value of a negotiation set can be calculated through an additive value function proposed in [27] or any other function. A value function may be considered as (5) [14].

$$\aleph^* = \{\Im_1, \Im_2, \ldots, \Im_{n-1}, \Im_n\} \tag{3}$$

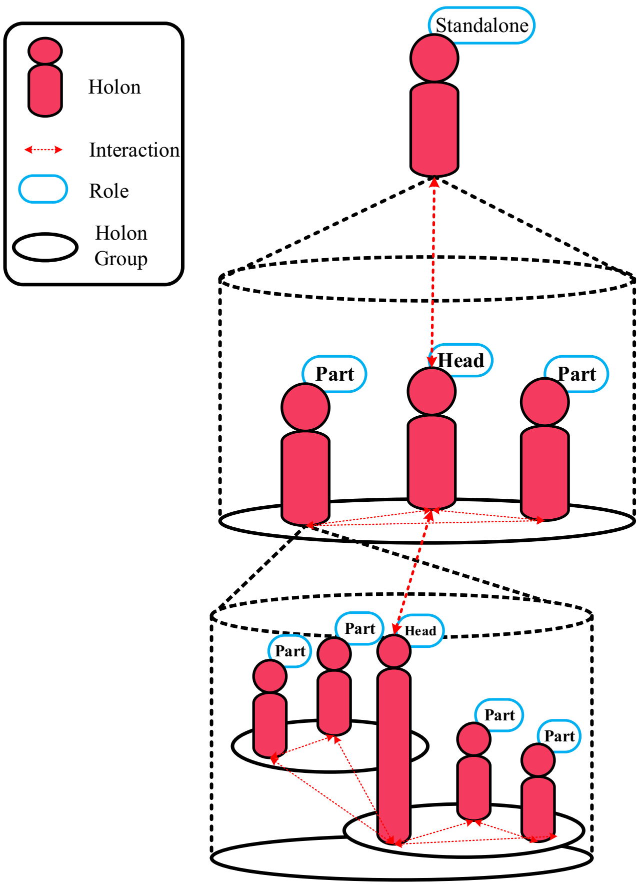

Fig. 3. Internal organizations of the Holarchy (Holonic organization).

$$\Gamma(I^{*}) = \{[\min(\Im_1), \max(\Im_1)], [\min(\Im_2), \max(\Im_2)], \ldots, [\min(\Im_{n-1}), \max(\Im_{n-1})], [\min(\Im_n), \max(\Im_n)]\} \tag{4}$$

$$\Re(\Im) = Objective\ Function\ of\ DORPC\ problem + \Im_{S\_H\_merging} + P_{S\_H\_merging} \tag{5}$$

where $\aleph^{*}$, $\Im_u$, Γ, $\Re$, and υ_q are the sub-set of issues, uth issue, permissible limit for each issue, value function, and the relative importance of qth issue, respectively. The $P_{S\_H\_merging}$ is indeed a coefficient for negotiation and merging between Holons. When this parameter takes a low value, Holons are willing to exploit the resources pertaining to the other Holons and to merge with each other. It goes without saying that if this trend continues, the Holonic structure will inadvertently transform to a centralized approach (which is in opposite to our aims). Consequently, this trend should be controlled by preventing some unnecessary merging processes. In this paper, this parameter is considered to be equal to 10. If a Holon wants to negotiate on an issue, a single function composed of Holon resources (HR_w) may be used to model the Holon value as (6) and (7):

$$\Im = \sum_{w=1}^{n} \beta_w f(HR_w) \tag{6}$$

$$so\ that \sum_{w=1}^{n} \beta_w = 1 \quad and \quad \beta_w \geqslant 0 \tag{7}$$

The HR can be controlled by Holons. In this paper, the reactive power is considered as HR. The $f(HR_w)$ models the relation between the resources and the Holon's issue. Meanwhile, different methods are employed to model it. This can be based on the Power Flow (PF) or decomposition methods described in this paper.

Formulation of the DORPC problem

Mathematically, the DORPC problem can be expressed as follows:

$$\min OF(UV, CP) \tag{8}$$

Subjected to

$$EC(UV, CP) = 0 \tag{9}$$

$$IC(UV, CP) \leqslant 0 \tag{10}$$

where UV, CP, $OF(UV,CP)$, $EC(UV,CP)$ and $IC(UV,CP)$ are vector of unknown variables, vector of control parameters, objective function, equality constraints and inequality constraints, respectively. In this paper, the OF is modeled as follow:

$$OF = \sum_{m=1}^{4} \wp_m \times OG_m \tag{11}$$

$$OG_1 = P_{loss} = \sum_{k \in N_L} G_k \left(V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij}\right) \tag{12}$$

$$OG_2 = \Delta V = \sum_{k \in N_B} \left| \left(V_b^i - V_b^{i^*}\right) \right| \tag{13}$$

$$OG_3 = VSM \tag{14}$$

$$OG_4 = \varphi_1 \sum_{z=1}^{N_{DG}} Q_z^{DG} + \varphi_2 \sum_{y=1}^{N_{CU}} Q_y^{CU} + \varphi_3 \sum_{c=1}^{N_C} Q_c^{C} + \varphi_4 \sum_{eV=1}^{N_{PEV}} Q_{eV}^{PEV} + \varphi_5 \sum_{tp=1}^{N_{TAP}} \Delta T_{tp} \tag{15}$$

where: OG_1, OG_2, OG_3, OG_4, N_{DG}, N_{CU}, N_{PHEV}, N_{TAP} are sum of active losses, sum of voltage deviations, voltage stability margin index, penalty function, number of DGs, number of conventional units, number of capacitors, number of PEVs and number of rap-changers, respectively. T_{tp}, Q_z^{DG}, Q_y^{CU}, Q_c^{C} and Q_{eV}^{PEV} are position of tpth transformer tap (integer), reactive power of zth DG, reactive power of yth conventional unit, reactive power of cth shunt capacitor and reactive power of evth PEV, respectively. V_b^i, $V_b^{i^*}$, Φ_i, VSM, G_{ij} and θ_{ij} are the voltage amplitude of ith bus, desired voltage value of ith bus, weight factor, voltage stability margin index, transfer conductance between ith bus and jth bus, and voltage angle difference between ith bus and jth bus, respectively.

Further details on the voltage stability margin index calculation can be found in [29]. Φ_i and φ_i can be determined based on the Holon resources and Holon conditions using different methods such as the sensitivity analysis. The OF is considered as the Holon's *utility* function. Holons try to minimize the objective function via negotiation and internal optimization. The constraints of the DORPC problem are as follows [30–32]:

$$P_g^i - P_d^i = V_b^i \sum_{j=1}^{n_i} V_b^j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \tag{16}$$

$$Q_g^i - Q_d^i = V_b^i \sum_{j=1}^{n_i} V_b^j (b_{ij} \cos\theta_{ij} - g_{ij} \sin\theta_{ij}) \tag{17}$$

$$V_g^{zz}|_{\min} \leqslant V_g^{zz} \leqslant V_g^{zz}|_{\max} \quad zz = 1, \ldots, N_G \tag{18}$$

$$Q_g^{zz}|_{\min} \leqslant Q_g^{zz} \leqslant Q_g^{zz}|_{\max} \quad zz = 1, \ldots, N_G \tag{19}$$

$$Q_{res}^{rr}|_{\min} \leqslant Q_{res}^{rr} \leqslant Q_{res}^{rr}|_{\max} \quad rr = 1, \ldots, N_{res} \tag{20}$$

$$T^{tp}|_{\min} \leqslant T^{tp} \leqslant T^{tp}|_{\max} \quad tp = 1, \ldots, N_{TAP} \tag{21}$$

$$V_l^{ee}|_{\min} \leqslant V_l^{ee} \leqslant V_l^{ee}|_{\max} \quad ee = 1, \ldots, N_L \tag{22}$$

$$S_{li} \leqslant S_{li}|_{\max} \quad li = 1, \ldots, N_{li} \tag{23}$$

where V_g^{zz}, P_g^i, P_d^i,V_l^{ee}, b_{ij}, Q_g^i, Q_d^i, n_i, Q_{res}^{rr}, N_{res}, N_G, N_L, S_{li} and N_{li} are voltage of *zz*th generator-bus, generated active power at *i*th bus, active power demand at *i*th bus, voltage of *ee*th load-bus, transfer susceptance between *i*th bus and *j*th bus, generated reactive power at *i*th bus, reactive power demand at *i*th bus, set of numbers of buses, reactive power of the *rr*th reactive power source, number of possible reactive power sources, number of generator buses, number of load buses, power flow in *li*th branch and number of branch, respectively.

A plethora of methods have been proposed for solving the DORPC problem. From a technical viewpoint, they can be classified to two categories: (1) methods which consider PF as a sub-problem in the optimization model [29,30]. In these methods, PF is conducted with variables specified by the optimization process and its results are utilized for the *OF* calculation; (2) methods which consider PF constraints directly in the problem [31,32]. From another view point, the aforementioned methods can be categorized to the centralized and decentralized classes. The former considers all variables together [30–32], while the latter divides them into several problems [7,33,34].

DORPC based on the Holonic structure

This paper propones a comprehensive MAS with organization proportional with architecture and aims of the smart grid. For this purpose, it is necessary to distinguish a differentiation between Holon aspect (the Holonic organization) and goal dependent aspect (the internal organization). In this section, first, the Holarchy structure proportional with smart grid is provided. The smart grid is divided to Holons which are composed of sub-Holons while it may be at the same time a part of a super-Holon at an upstream level. In smart grids, the lowest level of Holons called *atomic* Holons can be loads, energy resources, controllable equipment and etc. An appropriate structure to integrate smart grids' functions (e.g. distribution management with DGs, micro grids management, demand response (DR), demand side management, frequency control, voltage control and etc) is a fundamental challenge of smart grids clearly. The literatures pose the particular or combined solutions for each function. It is obvious that generalizing other functions to all problems or larger-scale problems looks to be a big challenge. This paper proposes a comprehensive organizational multi-agent system (Holarchy) in accordance with objectives and structure of smart grids. This is the main contribution of paper which is neglected in other literatures. In fact, this paper focuses on the present a comprehensive structure for smart grids which employed for DORPC problem typically. It is only a generic application of structure, so that it can be generalized to other operation aspects.

Since the smart grid is a complex system with a large number of components interacting with each other, its analysis simultaneously increases the complexity. For this reason, in this paper a method to reduce its complexity is proposed which studies the network at smaller manageable parts called "*view*". In this way, first a part of system, *view*, will be selected and a Holarchy will be defined accordance with it. To construct a Holarchy, it is necessary to evaluate two aspects of Holarchy at each *view*, i.e. the structural aspect (Holonic organization) and the behavioral aspect (goal dependent internal organization). Thus, the modeling of each *view* includes of two main phases:

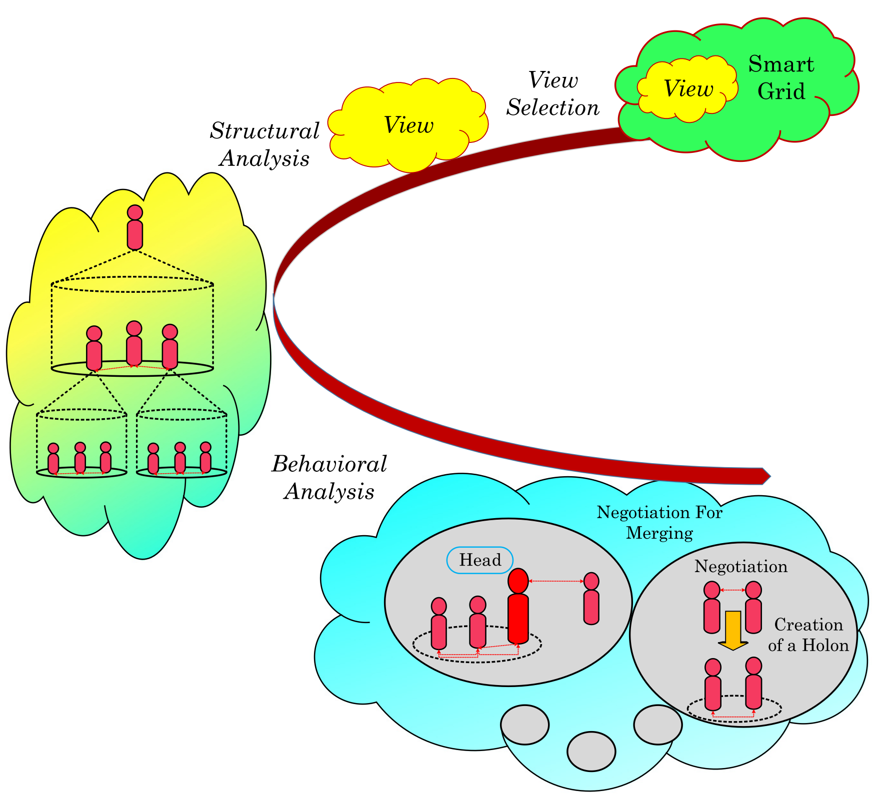

Fig. 4. The definition process of Holonic structure for the smart grid.

1. Structural analysis: In this step, it is determined that how engender the Holarchy structure and *views*' Holons.
2. Behavioral analysis: The behavior of a set of Holons are evaluated according to the defined roles, interactions and the organization. For example, the analysis of Holons' behaviors for DORPC of a distribution feeder.

A schematic plan of this process is illustrated in Fig. 4.

According to the definition presented above for Holon, a smart home can be smallest super-Holon which contains sub-Holons (*atomic* Holons) such as load, DGs, smart appliances, smart plugs, programmable communicating thermostats (PCTs), PEVs and etc. This is a general structure for Holarchy. In this paper, low voltage (LV) transformers are selected as lowest level super-Holon (LVT-Holon) which composed of *atomic* Holons such as smart homes, energy resources (capacitors or DGs), control equipment (tap changer) and advanced metering infrastructure (AMI) or measurement equipment. In this way, large-scale resources such as smart parks [35] (large-scale reactive power resources) and industrial customers are considered as a separate Holon. In an upper level, Holons located on a medium voltage (MV) feeder including LVT-Holons, DGs-Holons or reactive power resource-Holons comprise a super-Holon called MVF-Holon. In fact, each MVF-Holon supervises a part of MV feeder. Similarly, several MVF-Holons may form a higher level Holon called MVT-Holons. In fact, MVT-Holon manages a MV feeder encompassed of several MVF-Holons. These MVT-Holons also contain controller sub-Holons (tap changers, AMI and measurements). A distribution Holon (D-Holon) is defined as a super-Holon constituted of several MVF-Holons. This Holon is able to supervise MVF-Holons. In a higher level, several D-Holon located in a specified area consist a super-Holon called high voltage (HV) Holon (HV-Holon). In highest level, the energy management system (EMS) is considered as a master Holon (EMS-Holon). As explained earlier, in this decentralized organization, it is not necessary to communicate all data and commands to the EMS as proposed in ICS structure [7]. Therefore, Holons can supervise its members and internal organization to optimum the *OF* and negotiate with other Holons if it is necessary. In this structure, relation with upstream Holons will be executed only if all the Holon's actions (including reconfigurations, Holons' readjustments, negotiations results) in the downstream level are not sufficient. In this state, a request is send to the upstream Holon. In higher level, first related Holon analyzes situations and makes a decision. If necessary, it negotiates with other Holons in same level to participate them in the control process. This process continues to EMS level if problem still remains. This structure reduces additional communications between entities and declines the transferred data. Thus a less bandwidth will be necessary. Also, since all decisions are made in a lower level with less information, the processing time decreases. This increases the speed of reaction to the problem and reduces the possibility of instability of system. Fig. 5 shows the diagram of proposed structure in a power system.

The LVT-Holon can be communicates with other LVT-Holons and MVF-Holon through itself head or moderator Holon. Each Holon manages its internal interactions and tries to gain the Holon goals. In this paper, the *OF* defined in (11) is considered as the *utility* function of Holons. This can be extended to other goals of power system operation. The configuration of Holons can be

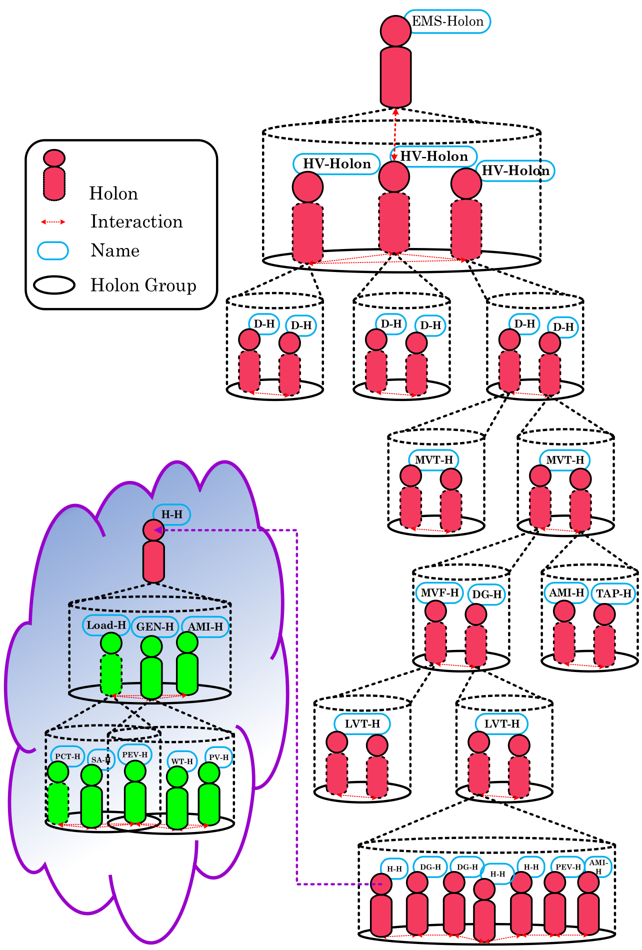

Fig. 5. The proposed Holonic structure for the smart grid.

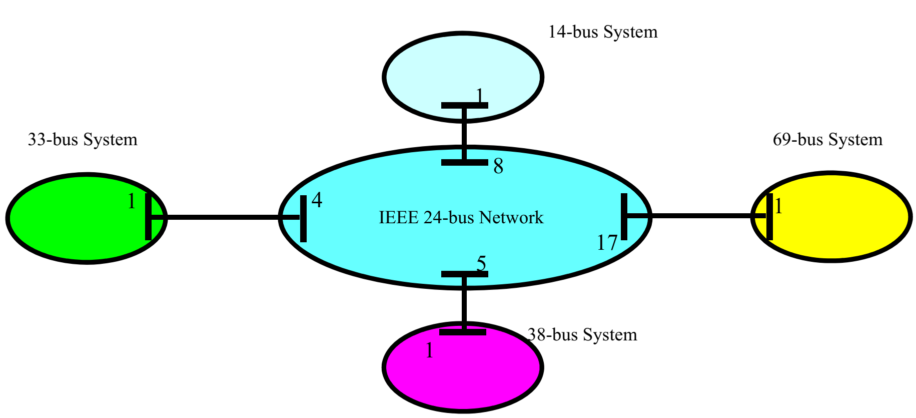

Fig. 6. The test system.

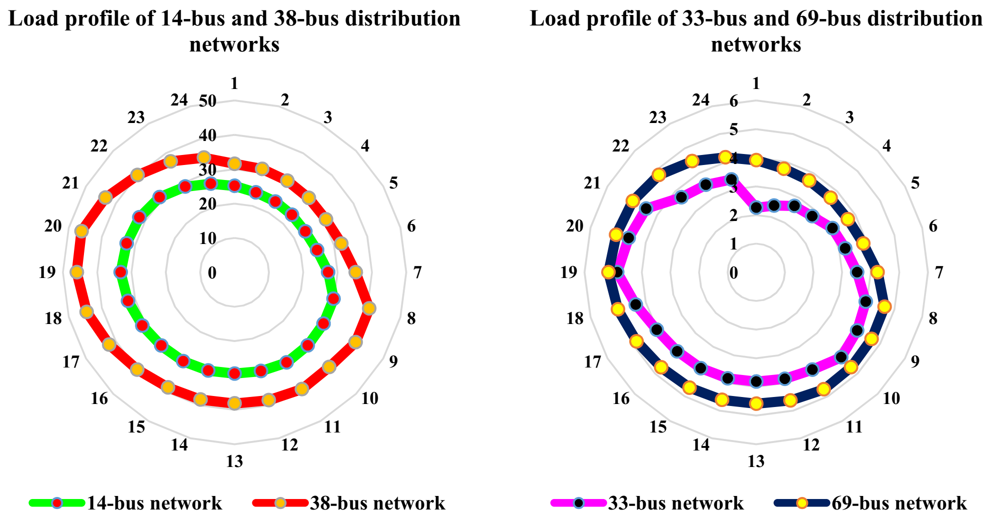

Fig. 7. The load duration curve of four distribution systems.

Table 1
The size and location of DGs and capacitors.

Equipment	Network	Bus	Size (kVA)	Equipment	Network	Bus	Size (kVA)
PV	14-bus system	5	250	Capacitor	33-bus system	13	60
Wind	14-bus system	10	600	Capacitor	33-bus system	10	40
PV	14-bus system	13	300	Capacitor	33-bus system	7	60
PV	33-bus system	15	275	Capacitor	33-bus system	33	60
Wind	33-bus system	22	250	Capacitor	33-bus system	28	60
PV	33-bus system	30	200	Capacitor	33-bus system	22	40
PV	38-bus system	6	330	Capacitor	33-bus system	25	30
Wind	38-bus system	14	880	Capacitor	33-bus system	6	40
PV	38-bus system	29	880	Capacitor	38-bus system	12	40
PV	38-bus system	34	250	Capacitor	38-bus system	18	60
PV	69-bus system	12	250	Capacitor	38-bus system	22	60
Wind	69-bus system	46	880	Capacitor	38-bus system	25	60
PV	69-bus system	50	250	Capacitor	38-bus system	33	30
Wind	69-bus system	66	250	Capacitor	69-bus system	9	30
Capacitor	14-bus system	3	80	Capacitor	69-bus system	14	40
Capacitor	14-bus system	4	80	Capacitor	69-bus system	22	60
Capacitor	14-bus system	7	80	Capacitor	69-bus system	28	60
Capacitor	14-bus system	9	40	Capacitor	69-bus system	36	60
Capacitor	33-bus system	18	60	Capacitor	69-bus system	43	40
Capacitor	33-bus system	16	40	Capacitor	69-bus system	14	40

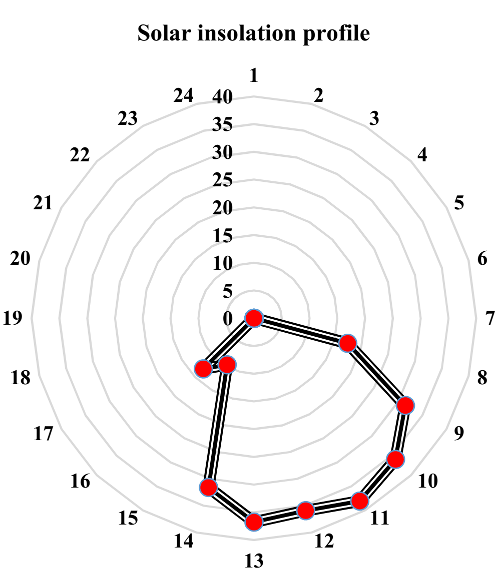

Fig. 8. The solar insolation data profile.

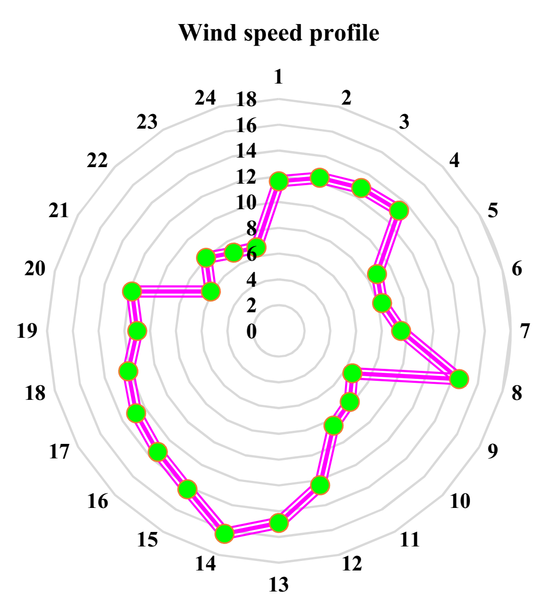

Fig. 9. The wind speed data profile.

changed according to different situations through negotiation of Holons' head. For example, if a LVT-Holon cannot satisfy its constraints using internal resources, the head negotiates with head of neighborhood Holon or upstream Holon based on (3)–(7). This negotiate can contain several issues. In this paper, the reactive power sources are considered *HRs* as defined in (7). It is possible that a sub-Holon from neighborhood Holon joins to primary Holon for control process or primary Holon integrates with neighborhood Holon or only some reactive power be transmitted between Holons. In fact, this dynamism is the key an advantage of Holon structures.

Similarly, Holon structure can be organized to HV level of system (transmission system). Thus, a hieratical distributed structure will be formed which can be employed for different goals of smart grids.

Formulation of the DGs and PEVs

In order to have more realistic results, the uncertainty of the RESs are taken into account in the simulations. Two common types of DGs are considered in this paper, i.e., photovoltaic (PV) and wind turbines (WTs). In a PV unit, the active power is calculated as, [36]:

$$P_{pv} = i_{pv}V_{pv} = N_p i_{pv} V_{pv} - N_p i_{rs} V_{pv}\left(e^{\frac{qV_{pv}}{N_s A K_0 T}} - 1\right) \tag{24}$$

$$i_{pv} = N_p i_{ph} - N_p i_{rs}\left(e^{\frac{qV_{pv}}{N_s A K_0 T}} - 1\right) \tag{25}$$

Table 2
The data of PV units, wind units and PEVs.

Parameter	Value	Parameter	Value
PV units			
N_p	1	N_s	13
T	25 °C	q	1.6×10^{-19} C
K_o	1.3805×10^{-23} J/K	E_{go}	1.1 eV
Wind units			
v_i	5 m/s	v_r	15 m/s
v_r	45 m/s		
PEVs			
V_{REC}	1	N_{PEV}	
AV_{MEC}	1500 kW h	REG_{PEV}	30%
$PARK_{PEV}$	94%	AV_{HLD}	2.0833 kW
X_{RL}	30%		

$$i_{rs} = i_{or}\left(\frac{T}{T_r}\right)^3 e^{qE_{go}/(1/T_r - 1/T)/AK_0} \tag{26}$$

$$i_{ph} = \frac{(i_{scr} + K_l(T - T_r))}{100}\lambda \tag{27}$$

where V_{pv} and i_{pv} are the output voltage and current of the PV array, respectively; N_p and N_s are the number of parallel and series cells, respectively; T is the cell temperature; the electric charge, the ideal P–N junction characteristic factor A = 1–5; i_{ph} is the light-generated current; i_{rs} denotes the reverse saturation current; and the intrinsic shunt and series resistances are neglected. i_{or} is the reverse saturation current at the reference temperature T_r; i_{scr} is the short-circuit cell current at a reference temperature and reference insolation 100 mW/cm^2; E_{go} is the band-gap energy of the semiconductor making up the cell; K_l (A/K) is the short-circuit current temperature coefficient; and λ is the insolation in mW/cm^2.

Also, the output power of WTs is calculated based on the wind speed and power formulation as follows [37,38]:

$$\begin{aligned} &P_{wind} = 0 \quad for\ v < v_i\ and\ v > v_o \\ &P_{wind} = W_r \frac{v - v_i}{v_r - v_i} \quad for\ v_i < v < v_r \\ &P_{wind} = W_r \quad for\ v_r < v < v_o \end{aligned} \tag{28}$$

where P_{wind} is the wind energy conversion system (WECS) output power (typical units of kilowatt or megawatt); W_r is the WECS rated power; v_i is the cut-in wind speed (typical units of miles/hour or miles/s); v_r is the rated wind speed, and v_o is the cut-out wind speed [38,39].

Practically, there are some limitations on the reactive power output of DG inverters [40]. Indeed, the permissible range of the reactive power output of DGs is modeled mathematically as follows:

$$\left|Q^{DG}\right| = \sqrt{\left(S^{DG}\right)^2 - \left(P^{DG}\right)^2} \ where\ P^{DG}_{\min} < P^{DG} \leqslant P^{DG}_{\max} \tag{29}$$

where S^{DG} is the apparent power of DG units. In order to have more realistic results, the prevailing uncertainties of the RES ought to be taken into account. To this end, the dependence of the PV outputs on the cell temperature and solar insolation are modeled in the proposed approach. The amount of generating power of PVs is calculated according to (25)–(28). The permissible range of the reactive power is calculated considering the active power and nominal capacity of DG units on an hourly basis.

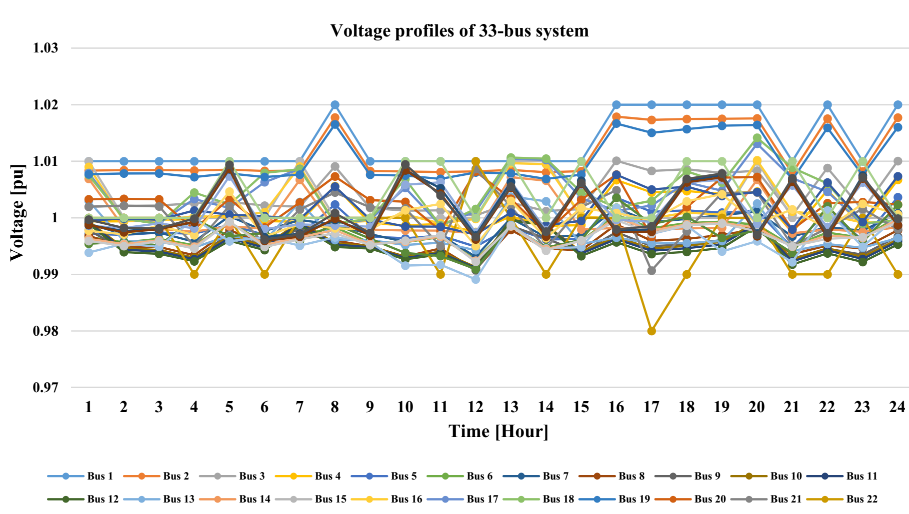

Fig. 10. The voltage profile of the IEEE 33-bus system.

As reported in [41], PEVs are parked almost more than 90% of the day and follow a daily schedule. On the other hand, such PEVs can be operated as a virtual static synchronous compensator (STATCOM) [35]. As a consequence, they have great potential which can be employed for the network control. Roughly speaking, reactive power can be injected to the network without significantly lowering the battery's state of charge (SOC). Hereupon, in this paper, PEVs are employed as a volt-ampere reactive (VAR) compensator which can absorb and generate VAR. The controllable capacity of PEVs' VAR is in the range of ±25.2 kVAR [35]. In practical cases, the number of PEVs in a power network can be estimated analytically based on the number of electricity clients (customers) [42]. In this paper, the number of PEVs for each load point of the network is calculated as follow:

$$N_{PEV}^{REPA} = PARK_{PEV} \times REG_{PEV} \times N_{PEV} \tag{30}$$

$$N_{PEV} = V_{REC} \times N_{REC} \tag{31}$$

$$N_{REC} = \frac{X_{RL} \times D_{\min}}{AV_{HLD}} \tag{32}$$

$$AV_{HLD} = \frac{AV_{MEC}}{30 \times 24} \tag{33}$$

where N_{PEV}^{REPA}, N_{PEV}, D_{min}, REG_{PEV}, $PARK_{PEV}$, V_{REC}, N_{REC}, AV_{MEC}, AV_{HLD} and X_{RL} are the number of parked PEVs registered in the reactive power compensation program as an ancillary service, the total number of PEVs for a load point, the minimum load of a load point, the percentage of registered PEVs in the mentioned program, the percent of parked PEVs, the number of PEVs per client, the total number of clients in the region, the average monthly electricity consumption of a domestic home, the average hourly electricity load of a

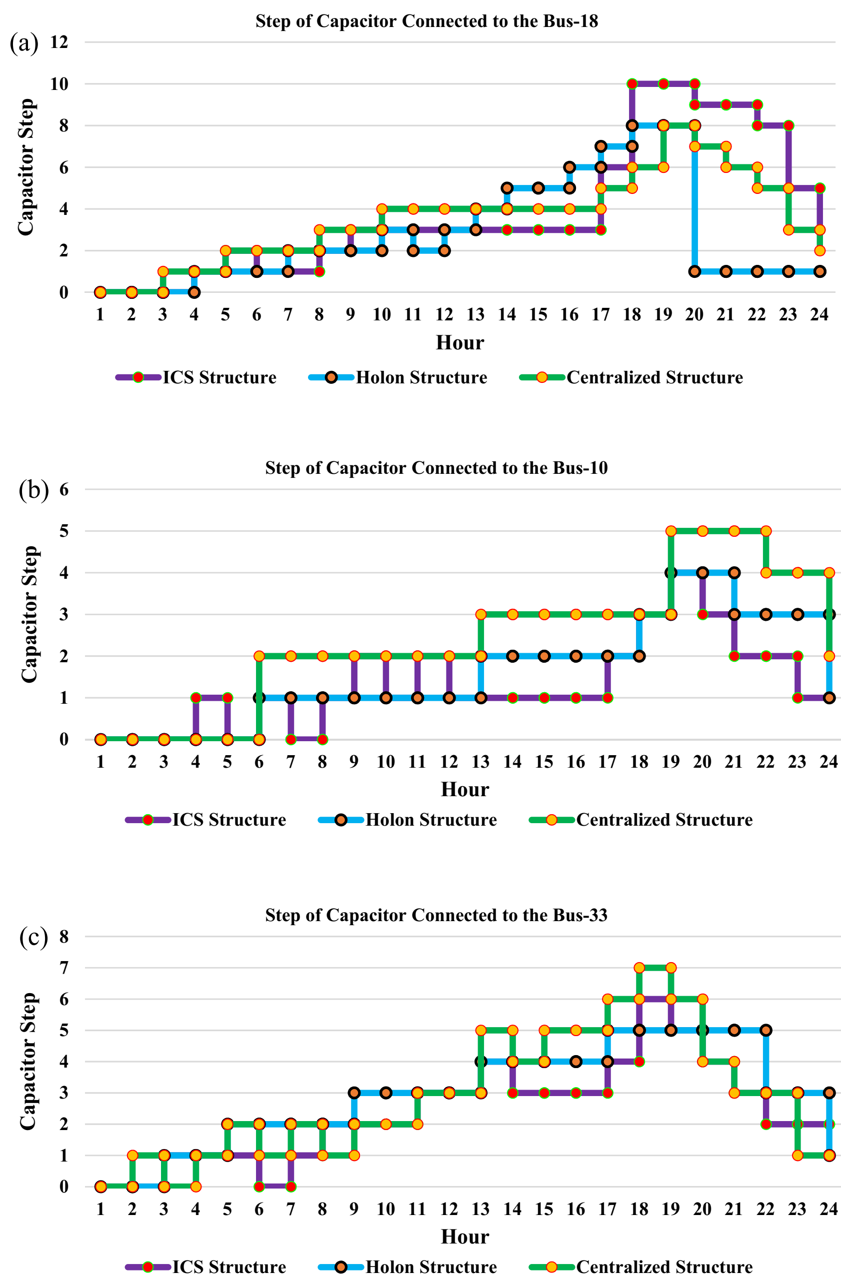

Fig. 11. Controllable variable values for 24 consecutive hours obtained by the proposed DORPC strategy.

residential client and the percentage of the residential loads in the power network.

Numerical studies

To evaluate the proposed strategy, a power transmission system connected to four distribution systems is used. The Holonic model of the case study is shown in Fig. 6. The IEEE 24-bus transmission system consists of 6 load buses, 11 generator buses, and 33 transmission lines [43].

In this section, the Holonic-based DORPC strategy is applied to the aforementioned case study. The load duration curve of the distribution systems is shown in Fig. 7. In this paper, several pieces of equipment including the tap-changer of the distribution transformers, conventional generators, DGs, and shunt capacitors are considered as the Holons. The DG units include PV plants and WTs. Table 1 shows the size and location of DG units and capacitors. It is assumed that all capacitors have 10 steps. The solar and wind units are simulated based on the proposed model in section 4. The solar insolation and the wind speed profiles are illustrated in Figs. 8 and 9, respectively [38,44]. The allowable margin of the reactive power is calculated through the active power and nominal capacity hourly. Finally, the data associated with the wind farms, solar power plants, and PEVs are provided in Table 2.

In order to evaluate the proposed method in a realistic environment, an appropriate simulation test bed is developed. In the proposed testbed, agents are modeled using a JADE platform while the power system is simulated by MATLAB software. The Holons' configuration and the negotiation process are performed based on the proposed methodology in the JADE software. In this way, if it is needed to solve the optimization problem, JADE send an optimization request along with the required information to MATLAB. These

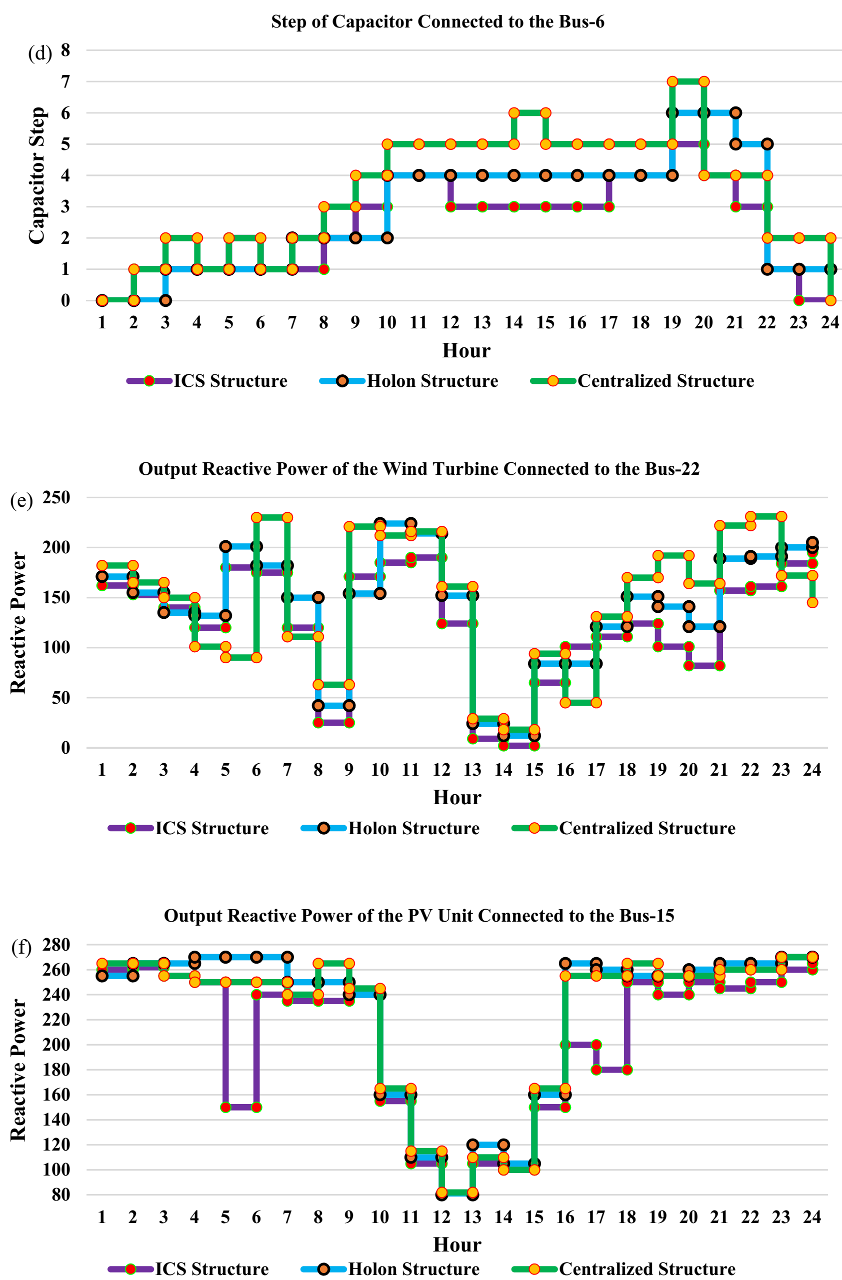

Fig. 11 (*continued*)

information may include Holons' configuration according to the Holonic architecture. Then, MATLAB software receives the information which is sent by JADE and the aforementioned optimization program is executed. Subsequently, the outcomes will be sent back to the JADE and this process will be continue until an optimum solution is obtained.

Using the proposed DORPC strategy, MVF-Holons use their reactive support resources effectively to minimize the objective function, based on their negotiations and internal defined priority list. The obtained voltage profile of the IEEE 33-bus distribution system is shown in Fig. 10. According to the obtained voltage profile, the proposed DORPC scheme can maintain the voltage values within an acceptable range.

As it was mentioned in the previous sections, Holons are able to utilize their own resources along with the resources pertaining to the other Holons (the latter is done through negotiations). This issue would lead to greater exploitation of the available reactive power resources. In this way, each Holon attempts to use its own reactive power resources so as to minimize the objective function while respecting the constraints. If the constraints are violated or if it is more economical to use the resources of the adjacent Holons, the Holons will negotiate with the aim of exploiting the resources pertaining to the adjacent and/or upstream Holons. Fig. 11(a)–(d) depicts the changes in the decision variables of the IEEE 33-bus system. Accordingly, the number of changes in the capacitors is more noticeable at the peak hours. This issue stems primarily from

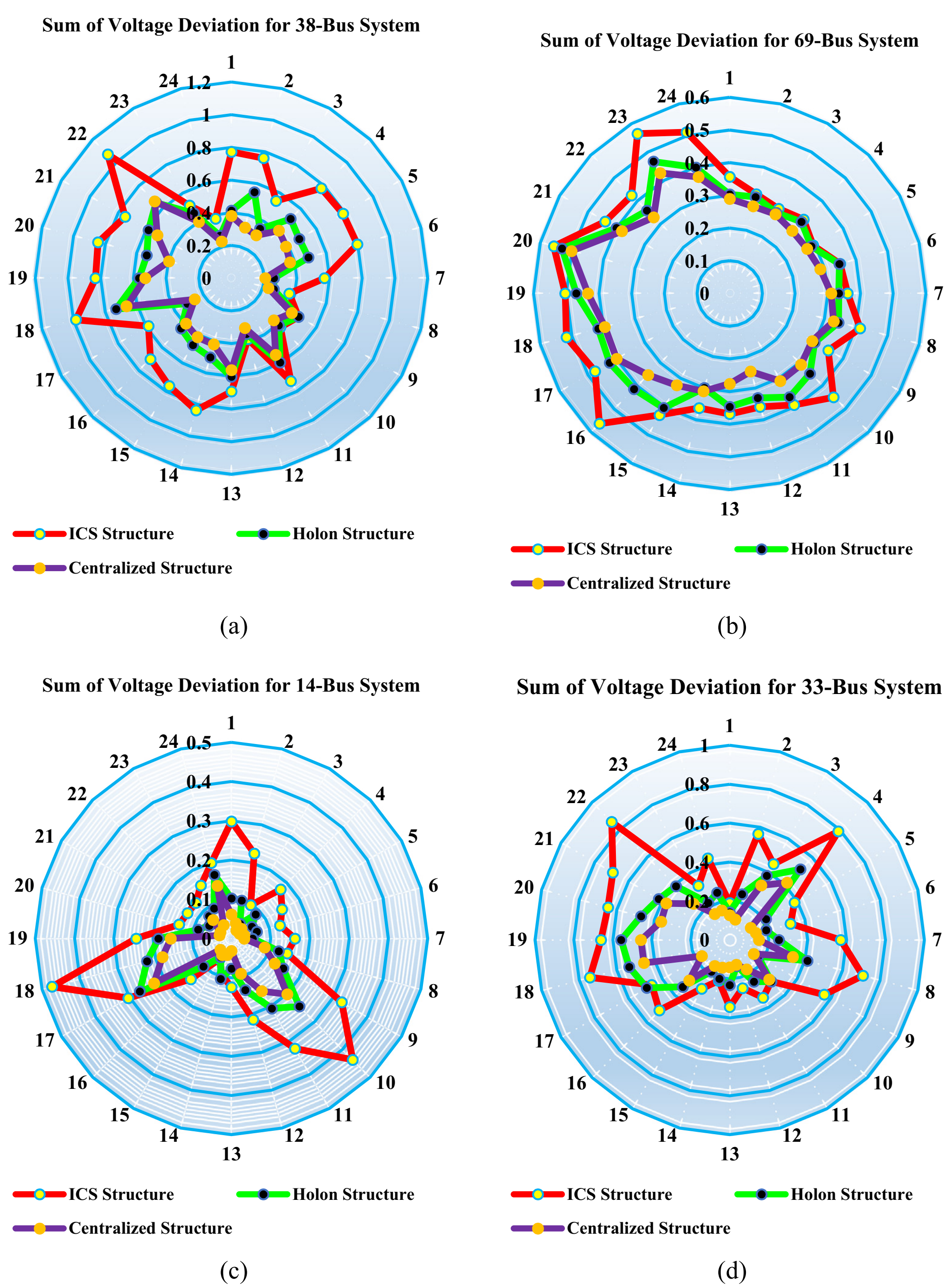

Fig. 12. The sum of voltage deviation obtained by three different methods.

the fact that Holons attempt to change the decision variables when the network is closer to its critical operating point. According to Fig. 11(f), the reactive power output of PV units decreases at midday owing to the fact that the active power output is at its highest level. On the contrary, in the begging and the end of the day, the reactive power output increases since the active power output diminishes. The same deduction holds true for wind turbines with regard to their wind patterns.

Fig. 12 shows the sum of voltage deviations for distribution networks, which is obtained from different strategies. It could be declared that the results obtained by the Holonic-based method is quite the same as the sum of voltage deviations obtained by the centralized method. However, as previously stated, the voltage deviation reduction through the Holonic architecture could be obtained in a low time-consuming process. Also, the proposed DORPC strategy leads to a dramatic improvement in the voltage deviations of the system compared to the ICS model.

From the active power loss viewpoint, it is necessary to analyze the proposed strategy in comparison to the centralized and the ICS methods. In Fig. 13, the amount of active power losses in distribution networks is illustrated calculated by various DORPC strategies. It is worth mentioning that the proposed Holonic-based strategy has a powerful performance to reduce the active power losses of the system compared to the ICS model. It is concluded that the proposed DORPC framework can control the reactive power flows to improve the active power loss, and voltage deviations using few control actions.

Burden of communication and computation

It is important for the control system to provide appropriate solutions within a short period of time. In the JADE environment, the size of the messages is 1500 bytes. In this case, it takes about 1–200 ms to send and receive a massage. In terms of efficiency, the DEA-based centralized structure takes 931 s for all simulations while ICS and Holarchy require less time. Obviously, the reason is that the volume of data to be processed in the decentralized structures is a lot less than that of a centralized structure. The processing time for three structures is given in Fig 14. According to this figure, the Holonic structure takes less time than the ICS

Fig. 13. The active power loss curve obtained by three different methods.

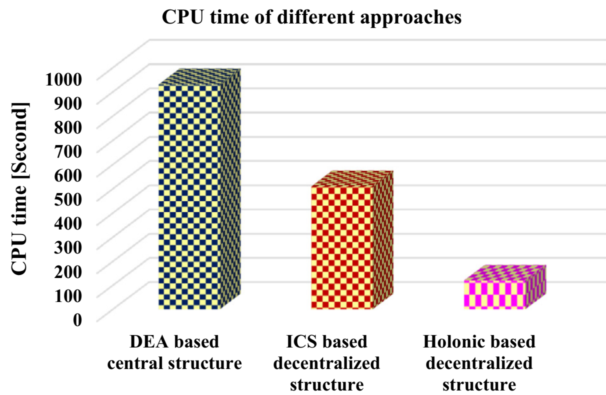

Fig. 14. The CPU time comparison for the test system.

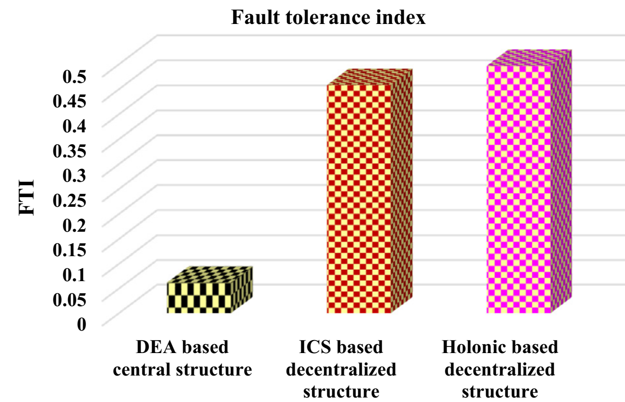

Fig. 16. The fault tolerance index of three structures.

structure to make a decision. This issue is mainly due to the additional communications between different layers in the ICS structure.

The throughput of the communication network is one of the most important indices in smart grids due to the numerous information entities with the communication capability. According to the Little's theorem [45], if a set of entities (i.e., Holon in the proposed structure) generates a data traffic at the rate of (λ_1, λ_2, ..., λ_{EN}), the overall aggregate throughput will be $OAT = \sum_{e \in EN} \lambda_e$. In the centralized control structures, *OAT* will be a large number. In this paper, the amount of data traffic load for the communication network is calculated based on data exchanged between Holons in the JADE software and it is presented in Fig 15. In this figure, the bar trajectories pertain to the left vertical axis, and the line trajectories are associated with the right vertical axis. As it can be seen, the centralized structure has the highest data traffic load due to the numerous entities. However, in the Holonic structure the information is exchanged locally, and only in the abnormal conditions, some information is sent to the Holons in the higher levels. Note that, owing to the fact that in the ICS structure the requests and commands must be validated by the EMS entity, the data traffic load is greater than the Holonic structure. In the centralized approach, entities should transfer their measurements to the control center and receive proportional commands; consequently, the data traffic load is constant, regardless of different conditions. On the contrary, in the proposed decentralized scheme, the data traffic load shows an adaptive pattern in accordance with the network load profile.

The fault tolerance is a vital factor in designing control structures. In this study, the index defined in [46] is used for modeling this characteristic. Fig. 16 contains the calculated fault tolerance

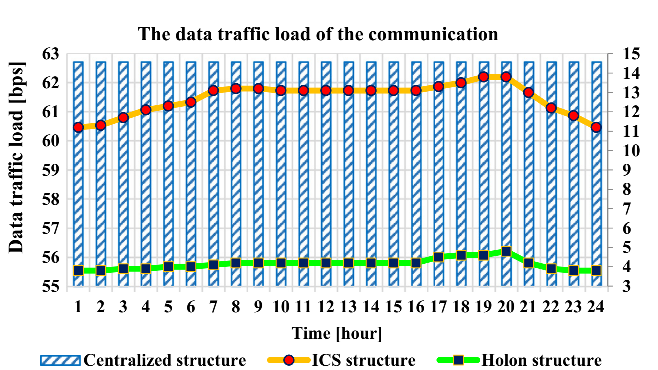

Fig. 15. The data traffic load of the communication network needed for the test system per bps.

index for the simulated structures. As can be seen, the centralized structure is much less fault-tolerant. This issue refers to its structure where all the entities are managed by a supervisory entity and its failure leads to an overall outage. However, in the Holonic structure, the lower levels can manage themselves even if the higher entity is failed. The less value related to the Holonic structure is due to its dynamism ability. In fact, if a Holon in a specific level is lost, its sub-Holons can be controlled by the neighboring super-Holons through merging them. Thus, the fault tolerance of the structure increases.

Conclusion

To alleviate the problems associated with the centralized control approaches, a novel decentralized framework for optimal reactive power control has been proposed in this paper. The framework is based on the Holons, which are evolving, self-organizing, and dissipative structures. A Holon is connected to other Holons, and at the same time, is nested within another Holon and so is a part of something much larger than itself. According to the rationale behind the proposed framework, it would fully exploit the available reactive power resources so as to keep the network security constraints. The novel method is tested on a comprehensive case study (including four distribution systems emanating from a transmission network), while the prevailing uncertainties are assiduously taken into account. The results indicate that the proposed DORPC strategy is more compatible with smart activities than the previous methods because of few control actions. Another beneficial result of this structure is its more improved computational efficiency. This issue leads to a decrease in the time of decision making process, and consequently, an increase in the stability of the network. Our simulation results have demonstrated that not only does the proposed structure have great potential to considerably save the communication bandwidth, but also the fault tolerance of the structure is increased due to the dynamic feature of Holons.

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